



## **Cognitive Systems**

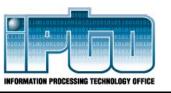
High Performance
Embedded Computing Workshop

Robert Graybill DARPA IPTO Sept 28, 2004

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**Report Documentation Page** 

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### The Challenge

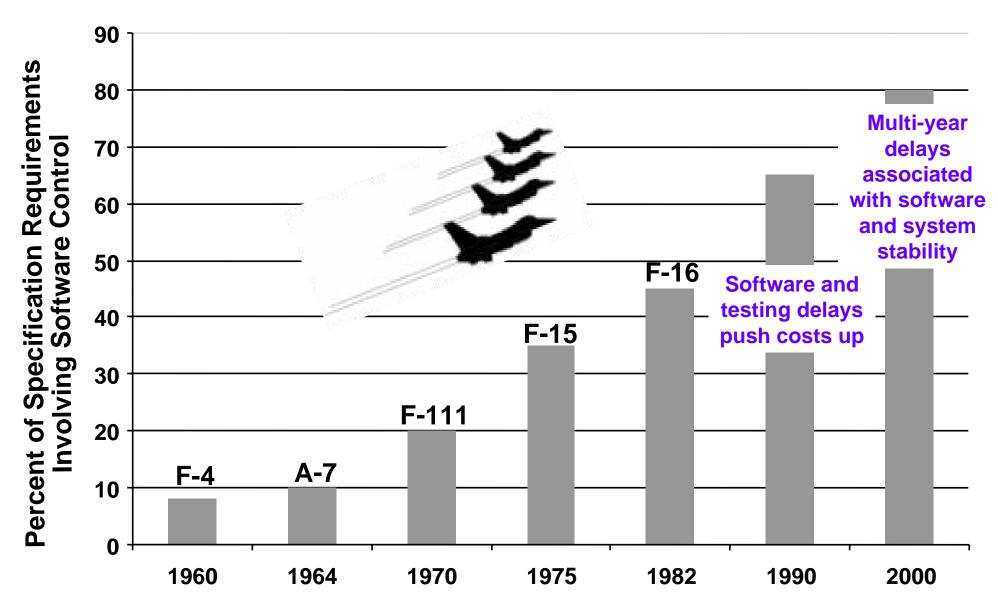


- Computer systems are the backbone of key national infrastructure and critical DoD systems
  - □ Virtually all important transactions involve massive amounts of software and multiple computer networks
  - **□ DoD** future vision is "network-centric warfare"
- While *computational performance* is increasing, productivity and effectiveness are not keeping up
  - □ Cost of building and maintaining systems is growing out of control
  - **□** Systems have short lifespans with decreasing ROI
  - **□** Demands on expertise of users are constantly increasing
  - □ Users have to adapt to system interfaces, rather than vice versa
- As a result, systems have grown more complex, more fragile, and more difficult to develop

We need to change the game



## Capability Provided by Software in DoD Systems is Increasing but so are the Challenges...



Ref: Defense Systems Management College 10/7/2004 RBG



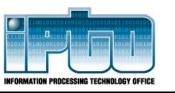
## **IPTO's Approach**



#### Developing Cognitive Systems:

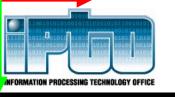
#### Systems that know what they're doing

- A cognitive system is one that
  - □ can reason, using substantial amounts of appropriately represented knowledge
  - □ can learn from its experience so that it performs better tomorrow than it did today
  - □ can explain itself and be told what to do
  - □ can be aware of its own capabilities and reflect on its own behavior
  - □ can respond robustly to surprise



# Computing Systems that know what they're doing can...

- DARPA
- ...reflect on what goes wrong when an anomaly occurs and anticipate its occurrence in the future
- ...respond to naturally-expressed user directives to change behavior or increase functionality
- ...be configured and maintained by non-experts
- ...reconfigure themselves in response to environmental changes and mission events
- ...reduce the effort to develop and maintain software
- ...thwart adversarial systems that don't know what they're doing
- ...preserve "corporate memory" to ease transitions for rotational personnel



#### Four Tiers of Agile Processing

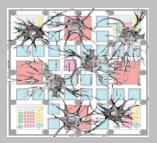


#### Systems That Know What They're Doing

What's Next?



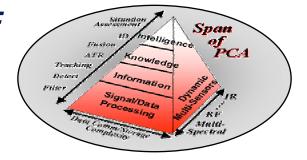
+ Cognitive Processing Hardware Elements **SBIRs** 



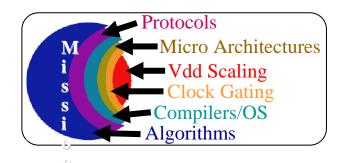
- **Intelligent Systems** 
  - Architectures for Cognitive Information Processing (ACIP)
- **High-End Application** Responsive Computing
  - ➤ High Productivity Computing Systems Program (HPCS)
- Mission Responsive Architectures
  - Polymorphous Computing Architectures Program (PCA)



+ *XPCA*??



- Power Management
  - Power Aware Computing and Communications Program (PAC/C)





#### **ACIP Program Vision**



Biological Clues
Cognitive Algorithm Clues
DoD Mission Challenge Clues

IPTO
Cognitive Efforts,
PAL, Real, SRS...

Functional
Demonstrations
& Algorithm
Developments

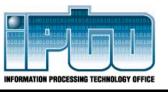
ACIP Phase 1
Early Architecture
Concepts & InContext Evaluation
- 2 Years -

ACIP Phase 2
Full Scale
Implementation and
Demonstration
- 4 Years -

ACIP Phase 3
Cognitive
Technology DOD
System Transitions
- 2 Years -

MTO
3-D Interconnects,
Optical, Nano

Physical Devices, Interconnect, and Packaging



#### **ACIP Phase I**



#### **Study Considerations**

**Metric Evaluation** 

#### **Deliverables**

Cognitive Reasoning, Learning & Knowledge Technologies

**In-Context** 

Cognitive

**DoD Applications** 

Cognitive Processing Requirements

DoD
Applications
Requirements
& Real time
Constraints

Innovative

**Architecture** 

Concepts

HW/SW Architectures & Technologies

**Multiple Disciplinary Teams** 

In-Context Evaluations

Analyze Cognitive Techniques, Computing, Memory and Control Requirements

Early
Architecture
Concepts

**Technology Assessments** 

(2 Year Study)

System architecture concepts, models, & evaluations-to-SDR

Concept device specification and technology roadmap

Cognitive computing requirements, analysis, specifications and runtime characterization

**Living Framework Draft** 

Composable runtime concepts

Phase II Challenge Problem, Metrics, & Go No/Go Definition

**MTO Technology** 

**IPTO Projects** 



#### **ACIP Phase I Response**



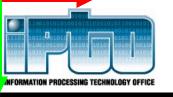
**■** Fantastic Response!!!

- Participation Mix (Including Subs)
  - **□** 9 Defense Contractors
  - **□** 11 Research Laboratories
  - **□** 51 Universities
  - **□** 30 Commercial Companies

Broad MultiDisciplinary
Coverage required
for System
Innovation

Large Diverse and Robust Teams Resulted in the Best Concepts

Study Technical Framework Concept has Emerged



#### **Funded ACIP Efforts**



- **COGnitive ENGine Technology (COGENT)** 
  - **□** Raytheon Company Network Centric Systems



- **Polymorphous Cognitive Agent Architecture (PCAA)** 
  - **□** Lockheed Martin Advanced Technology Labs



- **CEARCH:** Cognition Enabled Architecture
  - **University of Southern California/ISI**

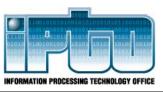




#### **ACIP Related SBIRs**



- Reservoir Labs Inc Cognitive Processing Hardware and Software elements
- Intelligent Automation Inc. Hardware Architectures for Flexible Component Based Hybrid Cognitive Systems
- Hoplite Systems LLC Cognitive Processing Hardware Elements
- Cardinal Research LLC Cognitive Processing Hardware Elements
- Saffron Technologies Associative Memory Hardware Elements for Cognitive Systems (Funded by AFRL)



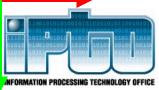
# Cognitive Technology Classification



Reasoning Algorithms  1st Order Reasoning  Shoutive Reasoning  Ray LM  Ray LM  Ist Order Reasoning  Ray LM  Ist Order Reasoning  Ray LM  Ist Order Reasoning  Ray LM  Ist Conder Reasoning		•			
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Maximum Likelihood       P       X         Meta-meta Reasoning       S       X         Modal Intuitionistic, Higher Order Reasoning       S       X         Model-based Reasoning       H       X         Non-monotonic Reasoning       S       Optimal decisions - Min-Max, Auctions       P       X         Pattern Matching       H       Y       Y         Probabilistic Constraint Satisfaction       H       X       X         Resource-limited Theorem Proving       S       X       X         SAT - Constraint Satisfaction       S       X         Special Purpose Reasoning Algorithms       S       X         Temporal Reasoning       S,P,H       X         Utility Theory       P       X	Markov Processes	Р			
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Model-based Reasoning       H       X         Non-monotonic Reasoning       S       S         Optimal decisions - Min-Max, Auctions       P       X         Pattern Matching       H       X       X         Probabilistic Constraint Satisfaction       H       X       X         Resource-limited Theorem Proving       S       X       X         SAT - Constraint Satisfaction       S       X         Special Purpose Reasoning Algorithms       S       X         Temporal Reasoning       S,P,H       X         Utility Theory       P       X		S			Χ
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Optimal decisions - Min-Max, Auctions Pattern Matching Probabilistic Constraint Satisfaction Resource-limited Theorem Proving SAT - Constraint Satisfaction Special Purpose Reasoning Algorithms Special Purpose Reasoning	Model-based Reasoning	Н	Χ		
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SAT - Constraint Satisfaction Special Purpose Reasoning Algorithms Special Reasoning		Н	Χ		Χ
Special Purpose Reasoning Algorithms     S     X       Temporal Reasoning     S,P,H     X       Utility Theory     P     X	Resource-limited Theorem Proving	S		Χ	Χ
Temporal Reasoning S,P,H X Utility Theory P X	SAT - Constraint Satisfaction	S	Χ		
Utility Theory P X	Special Purpose Reasoning Algorithms	_			Χ
Well-formedness Reasoning S X			Χ		
	Well-formedness Reasoning	S			Χ

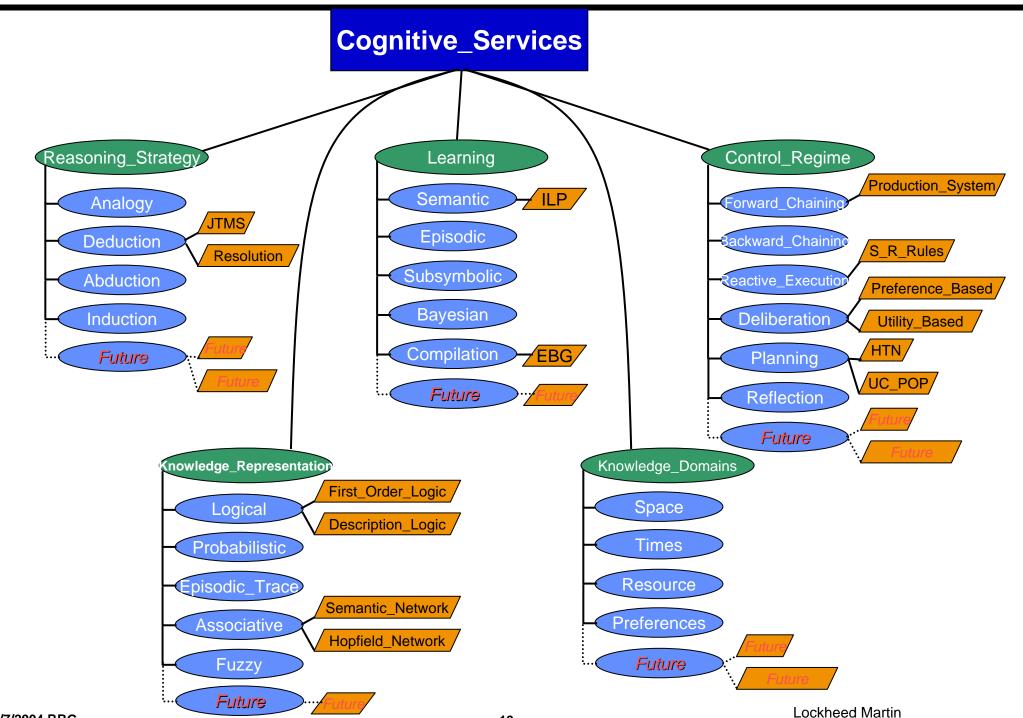
Learning Algorithms	Symbolic (S) Probabilistic (P) Hybrid (H)	Ray	LM	ISI
Abductive Learning	H	Ray	X	IOI
Abstraction	Н	Χ	٨	
	S	٨		Х
Analogical Learning Artificial Neural Networks	P		Χ	٨
Associative	H	Χ	٨	
Bayesian Learning	P	٨	Х	
Chunking	H	Χ	٨	
Classification Learning	Н	٨		
Clustering	P,H	Χ		
Constructing Analogies	F, F	Х		
Co-training Analogies	H	٨		
Data Mining	Н			
Decision Trees	Н		Х	
Dimensionality Reduction	H		٨	
Evolutionary Search	H			Х
Genetic Algorithms	P		Х	٨
Inductive Learning	S		Х	
Instance-based Learning	P		Х	
Learning from Advice	H	Χ	٨	
Network Construction	P	٨		
Parameter Learning	P	Χ		
Plan recognition	H	Λ.		
Reinforcement Learning	P,H	Χ	Х	Х
Relational Learning	S	Х		
Rule Generation Composition & Specialization	S	Λ.		
Statistical Clustering	P		Χ	
Statistical Learing (nearest neighbor, approx)	P			Χ
Supervised Learning	P			Х
Support Vector Machine	P	Χ		<u> </u>

Knowledge Representation	Symbolic (S) Probabilistic (P)			
Algorithms	Hybrid (H)	Ray	LM	ISI
1st Order Logic (with extensions)	S	Χ		Χ
Bayesian Classifier	Р			
Bayesian Networks	P,H	Χ		
Case -based	S			Χ
Causal Networks	Н	Χ		
Conceptual Graphs	Н	Χ		
Decision Trees	Н	Χ		Χ
Episodic	Н		Χ	
Frames	Н	Χ		
Fuzzy Logic	Н		Χ	
Horn Clause Program	S			
Influence Diagrams	Н	Χ		
Knowledge Acquisition	Н			
Logical (Prop., FOL, Frame-based)	S			
Logical Rules	S		Χ	
Markov Models	Р	Χ		Χ
Multi-layer Neural Net	Р			
Ontologies	Н	Χ		Χ
Production System	S			
Propositional Logic	Н	Χ		
Reactive Plan	S			
Relational Models	Н	Χ		
Rule-based Systems	Н			
Self-knowledge	Н			
Semantic Nets	S			
Situation Calculus	S	Χ		
Taxonomic Hierarchy	Р			
Temporal Networks	Н	Χ		
Type Ontologies and Constraints	S			Χ



### **Cognitive Services**







## **Cognitive Computing Requires Innovation**

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#### **Classical Computing**

- Markovian –current state only
- Processor-oriented; favors regular addressing
- Procedural, results oriented – apply this function next

- Key operations: arithmetic & simple scalar decision making
- Single deterministic result
- Parallelism difficult to extract
- Functional composition determined at compile time
- Largely static resource management

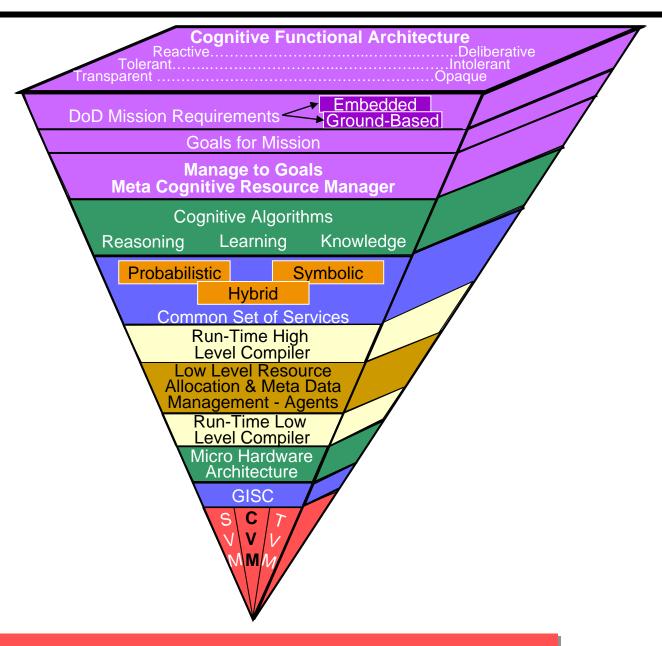
#### **Cognitive Processing**

- History of prior results guides next: "learning"
- Memory-oriented; unpredictable access patterns, with metadata guiding access
- Goal oriented with multiple, possibly incompatible objectives,
- Process oriented history + new perceptions => new knowledge
- Context oriented computation based on metadata from prior results
- Key operations: wide spectrum including complex pattern matching
- Often multiple "acceptable" results
- Speculation, futures a first class activity
- Functional composition determined at run-time
- Dynamic resource management (Reasoning vs Learning Balance)

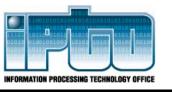


#### **ACIP Strawman Framework**





PCA (SVM+TVM) + CVM = ACIP???





#### **Potential New Research Ideas!**

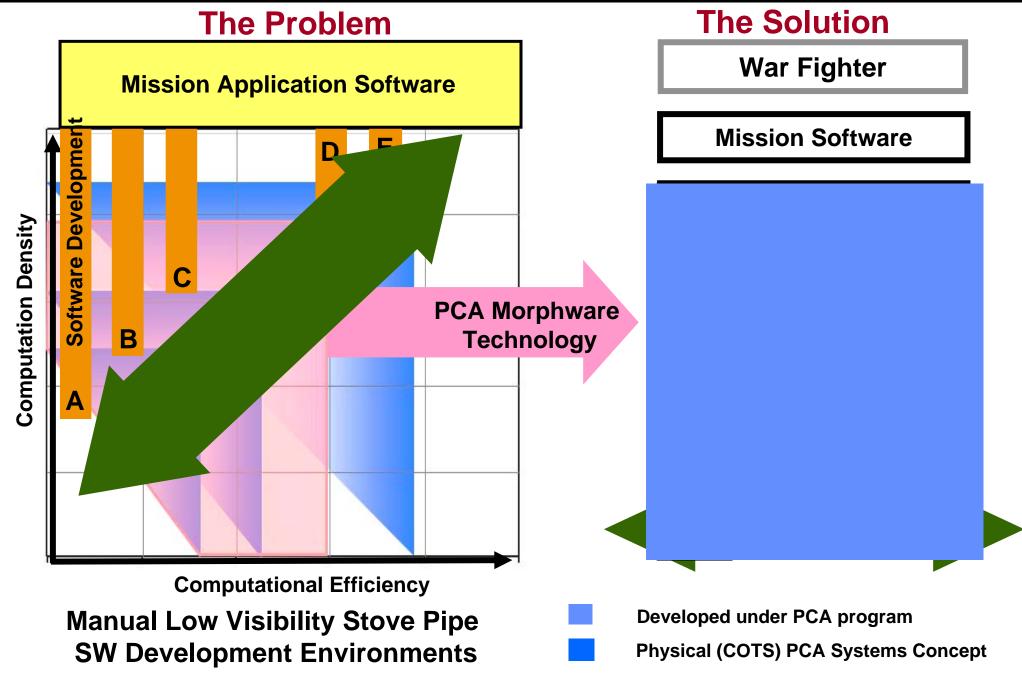
## **Leveraging Embedded Computing Workshop Ideas** Chaired by MIT LL and ISI

**Future Role of Embedded Computing Devices:** GP, DSP, GPU, NIC, FPGA, ASIC



### **Physical (COTS) PCA Systems**







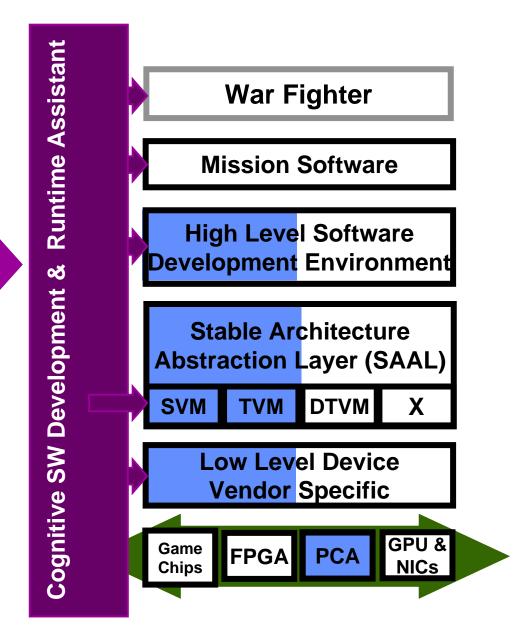
#### Software Developer's Assistant



## **Embedded Computing Complexity Challenge**

**Embedded Software Developer** 

The Solution:
Cognitive Software
Developer's Assistant





**Developed under PCA program** 





#### The Future is Yours

# Become an DARPA Program Manager!!